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CALIBRATION OF AN AXIAL FAN AT VARIOUS POWER SETTINGS FOR USE ON A QUARTER SCALE XC-8A AIR CUSHION MODEL

10 David L. Fischer, First Lieutenant, USAF

Mechanical Branch
Vehicle Equipment Division

11 Nov[redacted]80 12 49

TECHNICAL REPORT AFWAL-TR-80-3094

Final Report, [redacted] 1 Oct[redacted]77 [redacted]-1 May [redacted]79

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFWAL-TR-80-3094	2. GOVT ACCESSION NO. AD-A097 043	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) CALIBRATION OF AN AXIAL FAN AT VARIOUS POWER SETTINGS FOR USE ON A QUARTER SCALE XC-8A AIR CUSHION MODEL		5. TYPE OF REPORT & PERIOD COVERED Final Technical Report 1 Oct 77 - 1 May 79 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) David L. Fischer, 1Lt, USAF		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Flight Dynamics Laboratory (AFWAL/FIEM) Air Force Wright Aeronautical Laboratories (AFSC) Wright-Patterson AFB, Ohio 45433		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 24020104/0129
11. CONTROLLING OFFICE NAME AND ADDRESS		12. REPORT DATE November 1980 13. NUMBER OF PAGES 40
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release; Distribution Unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Air Cushion Landing Systems (ACLS)
Air Cushion
Fan Calibration

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A method was developed to measure volume flow from electrically powered fans during model testing of a dynamically scaled, quarter-scale XC-8A air cushion model. To measure the volume flow during model operation, the static pressure at a point along the fan inlet duct was correlated with volume flow. Correlation of the fan inlet static pressure with volume flow was performed using one of the two fans used on the model and a fan calibration rig. The fan calibration rig is independent of the model and used the orifice plate method to measure volume flow.

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Correlation was performed at five different input voltage settings to the fan from 100 volts/200 cycles to the normal rated voltage input of 200 volts/400 cycles. Reduction of the normal rated voltage was investigated so that the volume flow could be controlled during model operation to more accurately simulate the XC-8A fan performance maps.

The results of this work are five sets of graphical data illustrating the fan output static pressure and inlet static pressure versus volume flow. This data will be a key to future research using the quarter-scale XC-8A air cushion model for development of air cushion technology.

FOREWORD

This report describes the test procedure and results of an in-house research program conducted by the members of the Special Projects Group (FIEMB), Mechanical Branch (FIEM), Vehicle Equipment Division (FIE), Flight Dynamics Laboratory, Air Force Wright Aeronautical Laboratories, Wright-Patterson AFB, Ohio 45433. This work was accomplished under Project 2402, "Advanced Aircraft Vehicle Equipment"; Task 240201, "Mechanical Systems for Advanced Military Flight Vehicles"; Work Units 24020104 and 24020129, "Advanced Takeoff and Landing Systems Development/Test/Evaluation".

The work presented was performed during the period 1 Oct 77 through 1 May 79, under the direction of the author, 1Lt David L. Fischer, Project Engineer. Release of the report was by the author on September 1979.

In appreciation of their excellent support given during the program, the author wishes to thank Messrs David J. Pool, Shade Campbell, and Derrick A. Smith from the Special Projects Group (AFWAL/FIEMB).

This report is the first to be published under work unit 24020129. Future test reports in this area of research will follow advancing the technology of air cushion for use in takeoff and landing of aircraft.

TABLE OF CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

Symbol	Description	Units
ACLS	Air Cushion Landing System	----
C	Coefficient of discharge	non-dimensional
cfm	Volume flow	ft^3/min
d	Diameter of orifice throat	ft
F_a	Thermal expansion area factor	non-dimensional
Hz	Hertz	cycles per second
K	Flow coefficient	non-dimensional
P_1	Upstream orifice pressure	lbs/ft^2
P_2	Downstream orifice pressure	lbs/ft^2
Q	Volume flow	ft^3/sec
R	Gas constant for air	$ft^2/(sec^2\ °R)$
RPM	------	revolutions/minute
T	Temperature	degrees Rankine
Y	Expansion factor of gas	non-dimensional
β	Ratio of orifice throat diameter to pipe diameter	non-dimensional
γ	Specific weight	lb/ft^3
ρ	Density	$slugs/ft^3$

SUMMARY

At the completion of the XC-8A air cushion landing system (ACLS) advanced development program (695D), several problems were identified which required study. To determine the cause and develop solutions to these problems, model testing on an existing quarter scale dynamic model of the XC-8A is planned. To simulate the fan performance of the full scale XC-8A, the model fans must be capable of providing various amounts of volume flow. Measurement of the volume flow during model testing must be accurately determined and not affect the flow characteristics of the air flow.

Control of the volume flow can be achieved by varying the input voltage and frequency supplied to the two electrically powered axial fans used on the quarter scale XC-8A. For this investigation the voltage and input frequency was reduced in 25 volt steps from the normal value of 200 volts, 400 hertz to 100 volts, 200 hertz. At each of the five voltage settings, fan output volume flow was measured using one of the two model fans and a fan calibration rig. The calibration rig was designed for this test program and attached to the exit duct of one of the two fan units. The calibration rig is made of several sections of clear acrylic plastic tubing with an inside diameter of 8.25 inches to form a 203 inch duct. Located along the length of the duct are elements used to evaluate fan performance using the orifice plate method. Three different orifice plates with throat diameters of 6.5, 6.0, and 4.75 inches were used to cover the range of volume flows expected.

To measure the volume flow from the two model fans during model testing, fan static pressure at a point along the fan inlet duct was correlated with volume flow at the five input voltage settings. The inlet static pressure is a single value function of volume flow and can be accurately measured during model testing with negligible affect on fan performance. Data from testing showed a reduction in volume flow

for one fan unit from approximately 2,400 to 900 cubic feet per minute (CFM) at a fan output static pressure of about 0.45 pounds per square inch gauge (psig) within the steady flow range. The inlet duct static pressure varied from about -0.9 to -0.14 psig for the same drop in volume flow, respectively. The data gathered from this effort will be used in conducting future testing of the quarter scale XC-8A. Future testing with the quarter scale XC-8A ACLS model will include static fan performance, drop test, takeoff simulations, and landing simulations.

SECTION I

INTRODUCTION

The Flight Dynamics Laboratory from January 1974 through March 1977 conducted testing and evaluation of an Air Cushion Landing System (ACLS) on the XC-8A aircraft (Figure 1). From flight testing of this aircraft, several problems were identified that required further study to improve the operational capabilities of ACLS. To determine the cause of these problems and develop new design criteria for future air cushion systems, extensive model testing and analytical research is required. Prior to model testing, it is important that the characteristics of the fans used to provide air flow for the ACLS model are known. Parameters such as the amount of volume flow for a given fan pressure rise, regions of steady flow, and regions of stalled flow must be known. Also, it is desirable to control the volume flow output from the model fans. A change in the volume flow of air supplied to an ACLS will affect its performance. In order to recreate the full scale XC-8A test results with scaled model testing, the volume flow must be varied to meet different test conditions. Another advantage of being able to provide a range of air flow rates is to determine optimum values for various operational conditions.

The first objective of this in-house test effort was to develop a method to control the volume flow from the two fans used on the existing quarter-scale dynamic model of the XC-8A (Figure 2). The quarter-scale XC-8A model was used in preliminary tests of the ACLS for the full-scale XC-8A and will again be used in the investigation of the full-scale XC-8A problems. The second objective was to develop a method to accurately measure fan volume flow during model testing. The method used to measure fan volume flow must have an insignificant affect on the flow field in order not to alter the ACLS performance characteristics. The third and final objective was to experimentally determine the change in fan characteristics as a result of varying the output volume flow.

SECTION II

BACKGROUND AND APPROACH

The first objective of this test program was to develop a method to vary the fans volume flow of the fans used on the quarter-scale dynamic model of the XC-8A. Two electrically driven axial flow fans, that normally operate at a constant speed, support the air flow for the quarter-scale model. During preliminary testing of the quarter-scale model, two design points of volume flow were examined. The volume flow output from the fans was controlled by reducing the inlet area of the fan with restriction plates. This method was rejected for future applications because the restriction plates could not be changed during model operation. Also, small changes in volume flow would require a large number of restriction plates and tests to obtain the required data. After consulting with the manufacturer of the motor used in the fan unit, it was verified that lowering the voltage and frequency while maintaining the same ratio of volts to frequency as the design values of 200 volts/400 hertz, would reduce the fan RPM. By reducing the fan RPM, a corresponding decrease in the fan output volume flow will result. Lowering the input voltage and frequency to the fan motor will not harm the unit if the workload of the motor is intermittent as is the case in periodic model testing. Therefore, controlling the input voltage is a suitable method to control and provide a wide range of volume flows.

The second objective of this effort was to provide an accurate method of determining fan volume flow during model testing. The geometry of the air ducts, which direct the air flow from the fan exit to the ACLS trunk, are such that constant homogeneous flow could not be assumed with confidence. This precluded the use of a pitot tube to measure volume flow. Also, an orifice plate could not be used because the air flow characteristics changed by the orifice plate would alter the behavior of the ACLS. In a report by NASA (Reference 1), it was recommended that static gauge pressure at a point in the inlet duct could be correlated with volume flow to determine fan volume flow during model testing. The NASA work summarized in Reference 1 was accomplished in conjunction with prior testing of the quarter-scale XC-8A. NASA was aware of the problems in measuring volume flow during model testing. Static gauge pressure along the inlet duct is a single value function with volume flow and can be easily measured during model testing. The instruments required to record inlet static gauge pressure will not have a sufficient affect on fan or flow behavior. Considering these favorable factors, correlating the fan inlet static gauge pressure with volume flow was selected as the optimum test method.

To accomplish the last objective of this effort, a test setup had to be developed. The purpose of the testing was to determine the changes in fan characteristics with reduction of input voltage. The data gathered would be needed to determine the fan output volume flow as a function of the static gauge output pressure. Steady and stalled flow ranges would also be defined at the different input voltage settings. At the same time, the inlet static gauge pressure at a point in the inlet duct would be recorded to correlate it with volume flow. For a description of the resulting test setup, see "Description of Test Apparatus".

SECTION III

DESCRIPTION OF TEST APPARATUS

To measure the volume of air flow from a fan used on the quarter-scale XC-8A, a test setup had to be designed and fabricated. In previous work on the same type of fan by NASA (Reference 1), a test setup using orifice plates provided good results. The use of orifice plates is a widely accepted method to measure fluid flow. The equipment specifications and procedures are well documented by the American Society of Mechanical Engineers (ASME) (Reference 2). Since the NASA test setup was well documented and proved successful, a test setup similar to NASA's was designed and fabricated.

The fan calibration rig that was designed is made up of several sections of clear acrylic plastic seamless tubing with an 8.25 inch inside diameter and a .25 inch wall thickness. The tube sections were mated to provide a smooth, continuous surface and sealed to minimize the escape of any airflow. As specified in Reference 2, the applicable number of tube diameters was used to separate the various elements of the fan calibration rig. Figure 3 and 4 illustrate the layout of the elements which comprised the fan calibration rig. The flow straighteners are composed of 35 thin walled tubes approximately one inch in diameter and 16.5 inches long that were fixed to the inside of the tube. Three orifice plates of different throat diameters (Table 1) were fabricated to cover the anticipated range of air flows. They were made from .25 inch thick clear acrylic plastic and designed such that the orifice throat could be centered in the middle of the tube diameter when installed in the tube duct. A butterfly valve was located downstream of the orifice plate. The valve was constructed from a 1/8 inch thick metal disc that was bolted to a metal rod. The tube exit area could be varied by fixing the butterfly valve to one of 10 positions in 10 degree increments from 90° (fully open) to 0° (fully closed). Care was taken to minimize any vibration or shifting of position of the butterfly valve under load from the air flow to maintain a constant exit area.

When the butterfly valve was in the fully closed position, or provided the minimum exit area, the metal disc did not close off the pipe exit area to zero. A small exit area with the valve fully closed was provided so that high pressures would not damage the test apparatus or fan while conducting a test.

Three pressures were recorded during testing. Each pressure was measured using a differential type pressure transducer and constantly recorded on a Honeywell model 1508B visicorder. All the pressures were in terms of gauge pressure. This means that the pressure transducers measured the pressure difference between a peculiar test point and ambient conditions. One of the pressure measurements was taken at a point along the fan inlet duct wall (Figure 5). A hole was drilled perpendicular through the wall surface and a pressure tap mounted flush with the inside wall surface. This tap was 2.31 inches from the mouth of the bell inlet and in front of the fan blades. Note that the 2.31 inches does not include the distance between the outward face of the foreign object damage (FOD) screen and bell inlet. During testing, tape was wrapped around the gap between the FOD screen and bell inlet for additional FOD protection. The location of the inlet pressure tap is such that the pressure measured will be the static gauge pressure of the flow stream.

The other two pressures recorded were located one tube diameter (8.25 inches) upstream of the orifice plate and one-half diameter (4.125 inches) downstream of the orifice plate (Figure 3). The reference point of these distances is from the forward face of the orifice plate. These pressure taps were mounted perpendicular to the tube surface and flush with the inside wall. The type of pressures recorded were static gauge pressures. The location of these two pressure taps are in accordance with ASME specifications for measurement of the pressure drop across the orifice plate.

Other data recorded during each test were the ambient conditions and temperature of the air flow downstream of the orifice plate. The ambient pressure was measured using a mercury barometer prior to each test. Both ambient temnerature and temperature within the fan calibration duct were recorded continuously using a Honeywell-Brown Potentiometer model number Y153X60(P16)-X-61(V) and copper constantan wire. The air flow temperature within the fan calibration duct was measured at a point 45 inches downstream of the orifice plate (Figure 3).

The electrically powered axial flow fan was manufactured by Joy Manufacturing Company, Model AVRF85-62D1779, part number 500702-5380. It is driven by an electric motor rated at 15 HP, 11,400 RPM, 200 volts, three phase, 400 cycles (Figure 6).

SECTION IV

TEST PROCEDURE

To study the performance of the quarter-scale XC-8A axial fans, one of the two fans used on the model was removed from the model. The fan was then tested on the fan calibration rig described in Section III. It was assumed that both fans would have the same operating characteristics. Therefore, only one of the fans was evaluated.

The fan to be tested was mounted to the fan calibration rig such that the inlet was open to ambient conditions and the fan exit area was connected to the duct of the calibration rig. Data gathered during testing was used to determine the fan "characteristic curve" at different input voltage. This information was also used to correlate the static pressure at a point within the fan inlet duct to volume flow.

The "characteristic curve" of a fan shows the pressure drop across the fan as a function of volume flow. The pressure drop across the fan was equal to the static gauge pressure measured at one tube diameter (8.25 inches) upstream of the orifice. This pressure is also referred to as the upstream orifice pressure. Upstream orifice pressure is equal to the fan pressure drop since the inlet of the fan is open to ambient and the upstream orifice pressure is the difference between ambient and static pressure at that point. It should be noted that the pressure loss from the fan output to the upstream orifice pressure tap was assumed to be negligible. Volume flow was determined from the static pressure drop across the orifice plate, flow temperature, and orifice throat diameter (See Appendix for discussion of procedure used to determine volume flow). To vary the pressure drop across the fan, the exit area of the fan calibration rig was varied using a butterfly valve.

The normal test procedure was to start the fan and adjust the voltage input. Voltage input was adjusted to one of five levels (See Table 2) with the butterfly valve fully open. The butterfly valve was then varied in 10° increments from fully open (90° setting) to fully closed (0° setting) and then back again to fully open. For each butterfly position, the static gauge pressure one tube diameter upstream and one half tube diameter downstream of the orifice plate was taken. In addition, static gauge pressure from the inlet duct pressure tap, air temperature downstream of the orifice plate, and ambient temperature were recorded.

During several tests the butterfly valve was only closed to the 20° or 30° settings then returned to 90°. This was done since it was obvious that the fan was in an unsteady flow condition. During this unsteady operation, the downstream orifice pressure was greater than the upstream orifice pressure which made the data not useable. As the butterfly valve was closed, the input voltage would drop slightly due to the increased loading on the fan. No adjustment was made to return the voltage setting to the level at the beginning of a test run (butterfly at 90°) as the butterfly valve opening was varied. This procedure of not maintaining a constant voltage input with changes in butterfly opening was followed in order to evaluate typical operation of the fans during quarter-scale XC-8A model testing. During quarter-scale XC-8A testing, the input voltage to the fans will be set to a particular level. The model will then be dynamically tested as in a drop test or takeoff simulation. During dynamic testing there are no feedback controls (i.e., variable fan input voltage) to maintain a constant volume flow with changes in fan pressure drop. Therefore, to illustrate the fan characteristics during quarter-scale XC-8A model testing, the voltage input was not controlled as the butterfly valve opening was varied.

The fan was tested at seven different configurations using each of the three orifice plates listed in Table 1. Table 2 shows a matrix of the 21 test setups. The first fan configuration tested was at the normal input voltage and frequency of 200 volts/ 400 hertz with no restriction plate at the fan inlet. Figure 4 shows the fan with no restriction plate installed at the fan inlet. The second and third fan configurations were conducted using a large restriction plate (8.625 inches in diameter) and a small restriction plate (7.75 inches in diameter). The input voltage and frequency for both of these configurations was at 200 volts/ 400 hertz.

As discussed in Section II, "Background and Approach", during prior testing of the quarter-scale XC-8A, the model fans were trimmed for two different operating points of trunk pressure and volume flow using restriction plates at the fan inlet. The restriction plates reduced the area at the fan inlet, thereby decreasing the fan output volume flow. Figure 2 shows the model with a restriction plate installed on both fan inlets. The last four fan configurations were at reduced input voltages and frequencies as listed in Table 2 with no restriction plates installed at the fan inlet.

SECTION V

RESULTS & DISCUSSION

The first step in calibrating the axial fan for use on the XC-8A quarter-scale model was to verify and check out the calibration apparatus. Two sources of data for comparison with some of the test results were available. A characteristic curve which showed the fan exit static gauge pressure versus the volume flow of air was obtained from the manufacturer of the fan unit (Joy Manufacturing Company). Additional data of the same type was also available from Bell Aerospace. Bell's data was gathered in connection with calibration work performed during preliminary testing of the quarter-scale XC-8A using restriction plates to control the amount of air flow (Reference 3).

Reasonable data correlation was obtained between the fan manufacturer, Bell Aerospace, and the current study. This resulted in a high confidence level in the test setup and data reduction method. Since no data base on fan operation at different input voltage levels existed prior to the present study, this verification was considered necessary. Figure 7 illustrates the comparison between the manufacturer's characteristic curve and test results from this study. The test results conducted during this effort were run with no restriction plate at the fan air intake and with an electrical input to the fan motor of 200 volts/400 cycles. Note that the ordinate is labeled as upstream orifice pressure. It was assumed during this study that the pressure measured at this point was equal to the fan output static gauge pressure. The manufacturer's fan characteristic data, in terms of fan output static gauge pressure, was then plotted on the same graph to show the comparison.

Figures 8 and 9 compare the data from Bell's testing with the data from this study. The testing done by both Bell and this effort used two different size restriction plates to reduce the volume flow of air. A large disc measuring 8.625 inches in diameter and a smaller disc measuring 7.75 inches in diameter reduced the inlet area by 58.42 sq inches and 47.17 sq inches, respectively. The Bell calibration method involved entrapping the air flow as it was exhausted from the quarter-scale XC-8A model. The air entrapped was then allowed to exit through a duct which contained an orifice plate so that the volume flow could be determined. The electrical input for the fan was the normal operating setting of 200 volts/400 cycles. A good comparison was achieved between the two sets of data and confirmed credibility of the test and data reduction method. The slight differences between the data can be attributed to differences in instrumentation and/or test procedures.

Figures 10-13 show the volume flow versus upstream orifice pressure (assumed equal to the fan output static pressure) at the four input electrical settings from 175 volts/350 hertz to 100 volts/200 hertz with no inlet restriction plate. The curves were sketched through the data points using engineering judgment as to the accuracy of each point. The criteria for the accuracy of each data point is as follows.

The flow coefficient (k) calculated to determine volume flow is a function of the orifice diameter ratio (β) and Reynold's number of the flow. As the Reynold's number of the air flow decreases, which corresponds to decreasing volume flow and the orifice diameter ratio (β) increases, the error in the calculation of flow coefficient increases Also, as the volume flow is reduced, the pressure drop across the orifice plate decreases. This results in very small changes in pressure drop for a given change in volume flow and increases errors in the calculation of volume flow. Therefore, as specified in the ASME code for use of orifice plates, volume flows below 1,500 CFM and 1,000 CFM for the 6.5 and 6.0 inch diameter orifice plates, respectively, lose validity. This is why the 6.5 inch orifice plate is not shown for the 100 volt/200 hertz case. Data recorded for each orifice plate reached a maximum value of volume flow for one fan configuration. This maximum value increased as the orifice diameter increased and shows the need for a range of orifice throat diameters. Some of the volume flow data points exceeded the estimated useable range of volume flows as listed in Table 1. It should be noted that even though the data points exceeded the estimated useable flow range, they are still valid data points. A composite of the curves for each electrical input with no restriction plate at the air intake is shown in Figure 14.

Figures 15-21 show the static gauge pressure at the inlet duct tap versus volume flow. The curves for these graphs were sketched using the same guidelines for validating data points as used for the previous characteristic curves. The shape of these curves illustrate that the static pressure measured at the inlet pressure tap is unique with volume flow for each voltage setting. Figure 22 is a composite of the curves drawn for each voltage setting with no restriction plate. It can be seen that the inlet pressure varied slightly with constant volume flow over the range of voltage inputs. The reason for this variance is believed to be caused by changes in the velocity gradient normal to the fan inlet at different fan RPM.

SECTION VI

CONCLUSIONS & RECOMMENDATIONS

At the start of this test program, three objectives were to be resolved from the results of this work. First was to develop the capability to experimentally determine the characteristic curve of different fan units that would be used in conjunction with future ACLS model testing. The second objective was to evaluate the use of lower voltage settings on the axial fans to provide the capability to vary the volume flow output from the fans. Control of the fan volume flow was sought so that the changes in volume flow of air could be evaluated on the quarter-scale XC-8A so that the quarter-scale model would more closely duplicate full scale performance. The third and final objective was to obtain data so that the volume flow from the fans could be measured while operating on the quarter scale XC-8A.

The test rig that was designed and built for this study proved to be an excellent method for calibration of fans. The unit provided good fan characteristic data which was verified by comparison with other test sources. The part of the test setup which proved to be the most critical was the instrumentation. After review of some test data, it was determined that the results were erroneous because of faulty equipment. It is strongly recommended that great care be taken to verify the accuracy of all instruments prior to each test.

The three orifice throat diameters selected proved to be good for the range of volume flows expected. If further experiments using these fans is performed, it is recommended that an orifice throat diameter of 5.25 inches be included. The use of orifice throat diameters below 4.75 inches would not be required unless an investigation in the unsteady range of fan operation is required.

Operation of the fans at below design input power was successful. However, it is recommended that the power not be cut below 50 percent.

The reason for this limitation is that the fan is operating in a small range of steady flow and fan stall could become a problem. The steady flow region of an axial fan is when the volume flow is greater than the value of volume flow at the fan peak pressure rise or peak exit pressure. Care should be taken during operation of the fan to insure that fan stall will not interfere with model testing. Model testing while operating in fan stall is not a recommended practice.

Use of the fan inlet pressure to measure volume flow should prove to be an acceptable method. The location of the pressure tap on the fan is fixed so that position error will not result if the data from these tests are used. The inlet pressure is, as expected, a single value function of volume flow. Therefore, if the curves for inlet pressure are used in conjunction with the characteristic curves, a determination can be made if the fans are operating in the steady flow region during model testing.

TABLE 1

ORIFICE SIZES AND FLOW RANGES

Orifice Diameter (inches)	Estimated Useable Flow Range (cfm)
6.5	1500 - 2500
6.0	1000 - 2000
4.75	500 - 1000

TABLE 2

TEST MATRIX

Input Voltage/Frequency(Hz)	Restriction Plate	Orifice Diameter(In)
200/400	none	6.5
200/400	none	6.0
200/400	none	4.75
200/400	large	6.5
200/400	large	6.0
200/400	large	4.75
200/400	small	6.5
200/400	small	6.0
200/400	small	4.75
175/350	none	6.5
175/350	none	6.0
175/350	none	4.75
150/300	none	6.5
150/300	none	6.0
150/300	none	4.75
125/250	none	6.5
125/250	none	6.0
125/250	none	4.75
100/200	none	6.5
100/200	none	6.0
100/200	none	4.75

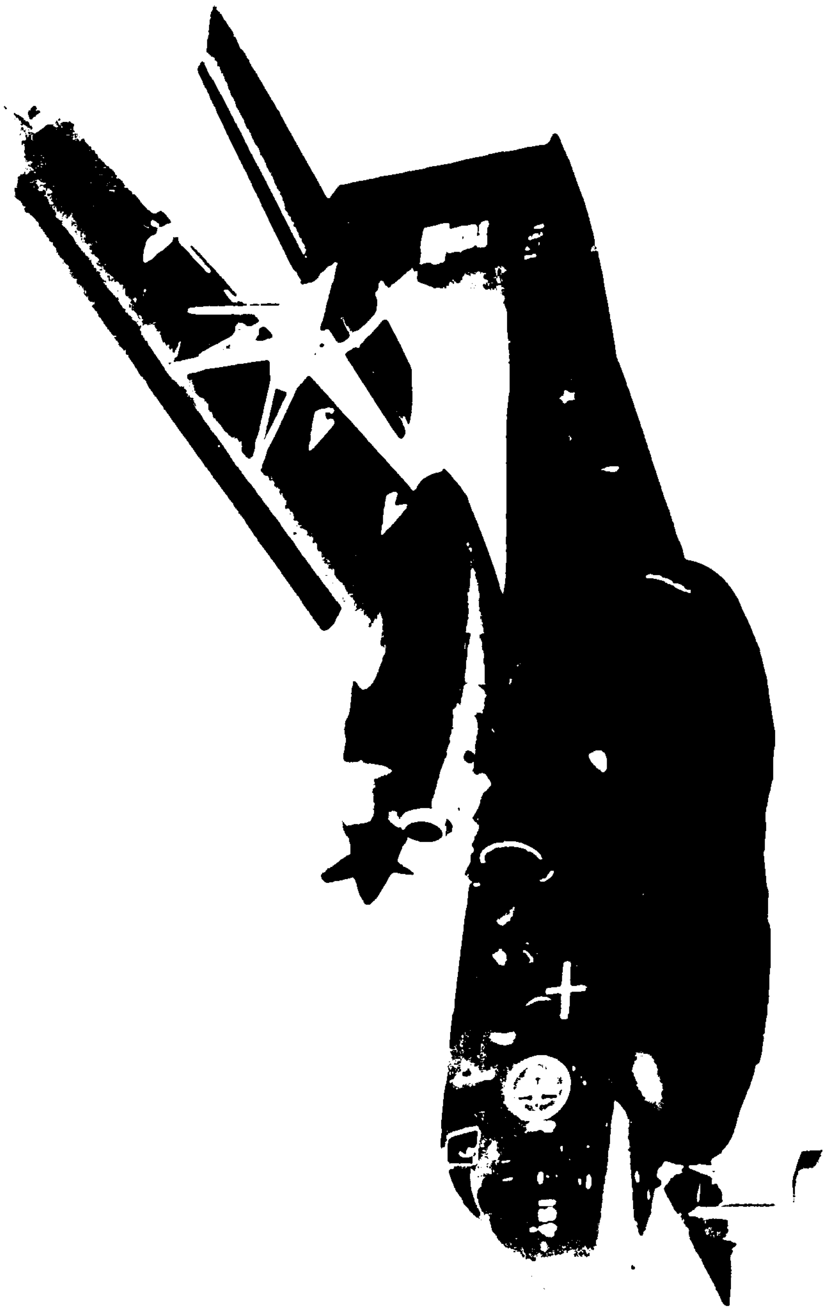


Figure 1. XC-8A Aircraft In-Flight with Trunk Inflated

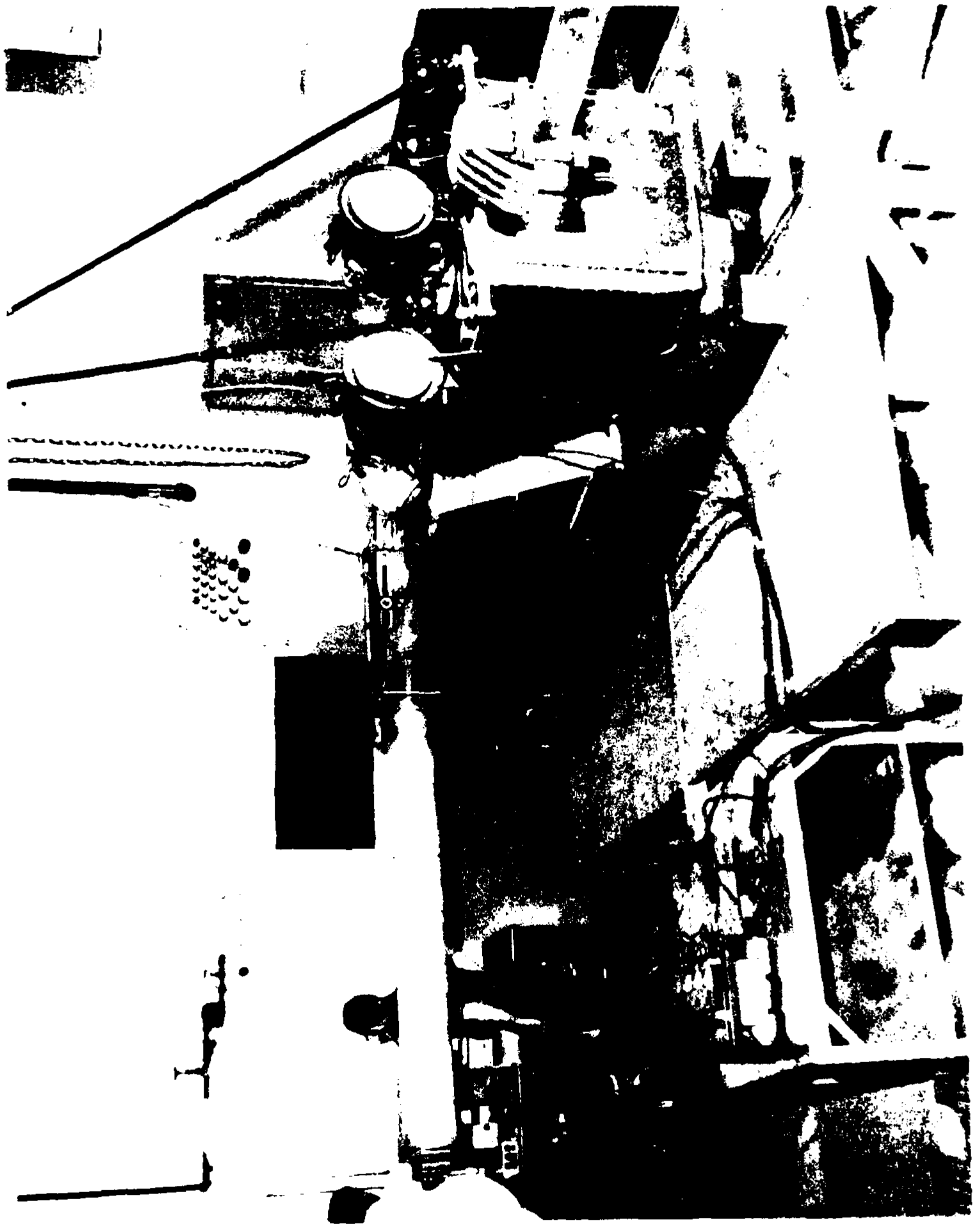


Figure [illegible]. Burner [illegible] Model

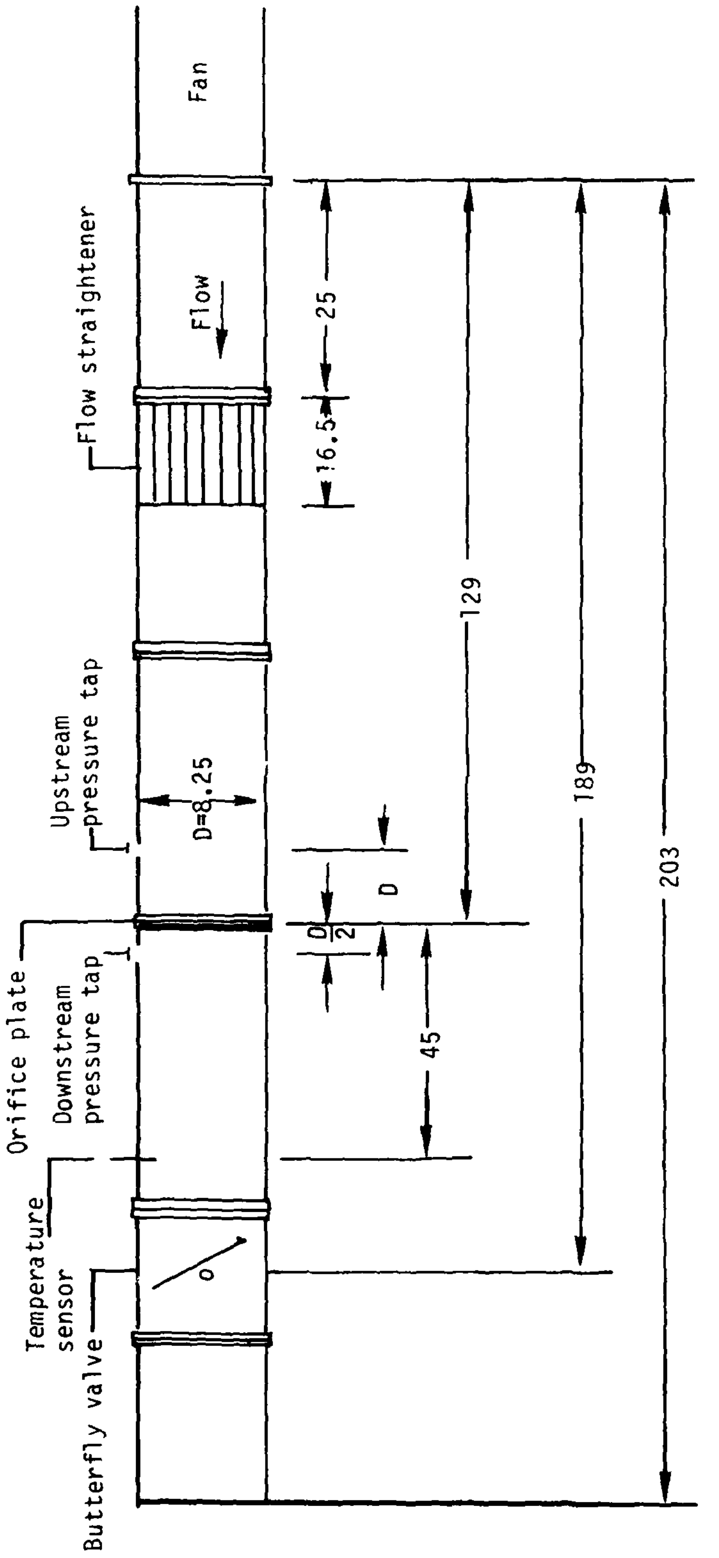


Figure 3. Schematic of Fan Calibration Rig (Dimensions are in Inches and Are Not Drawn to Scale)

Figure 4. Fan Calibration Rig

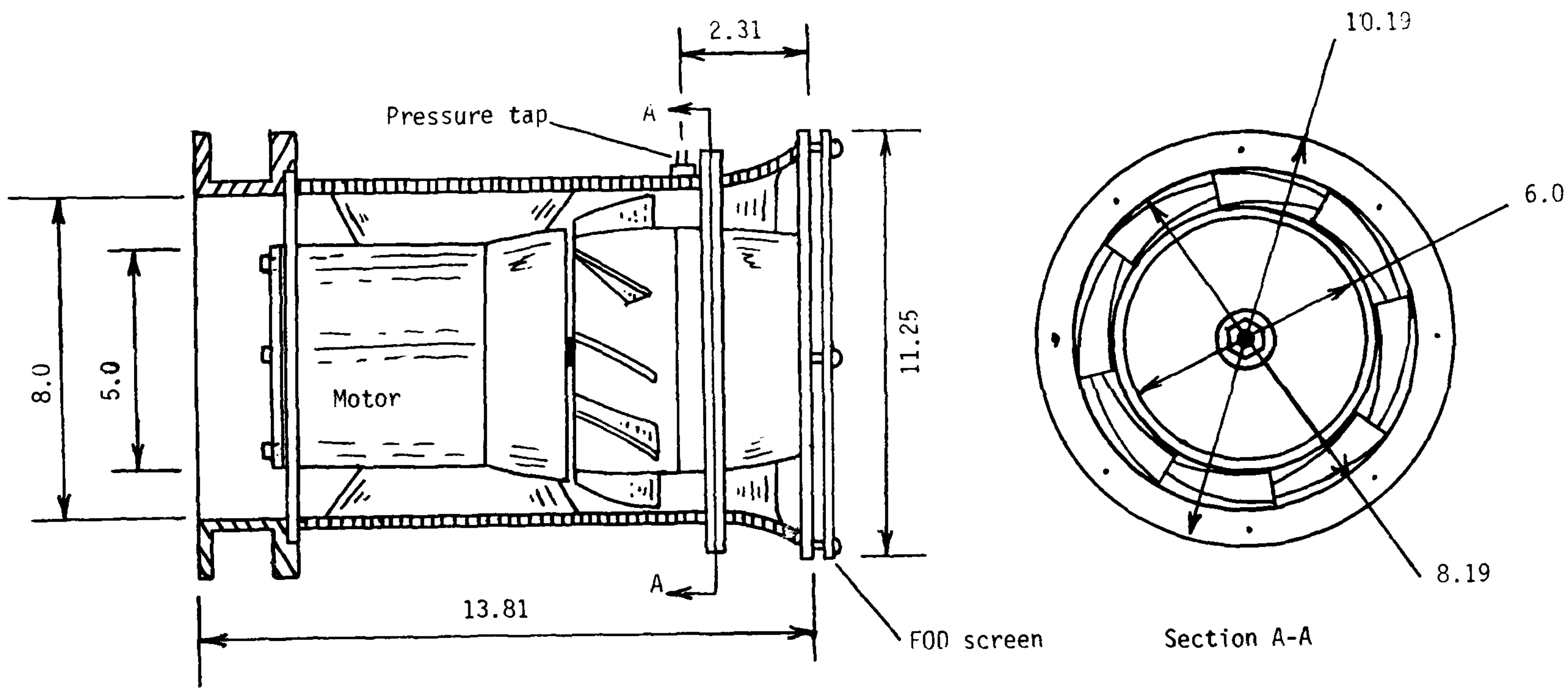


Figure 5. Schematic of Axial Fan Used in Testing (Dimensions are in Inches)

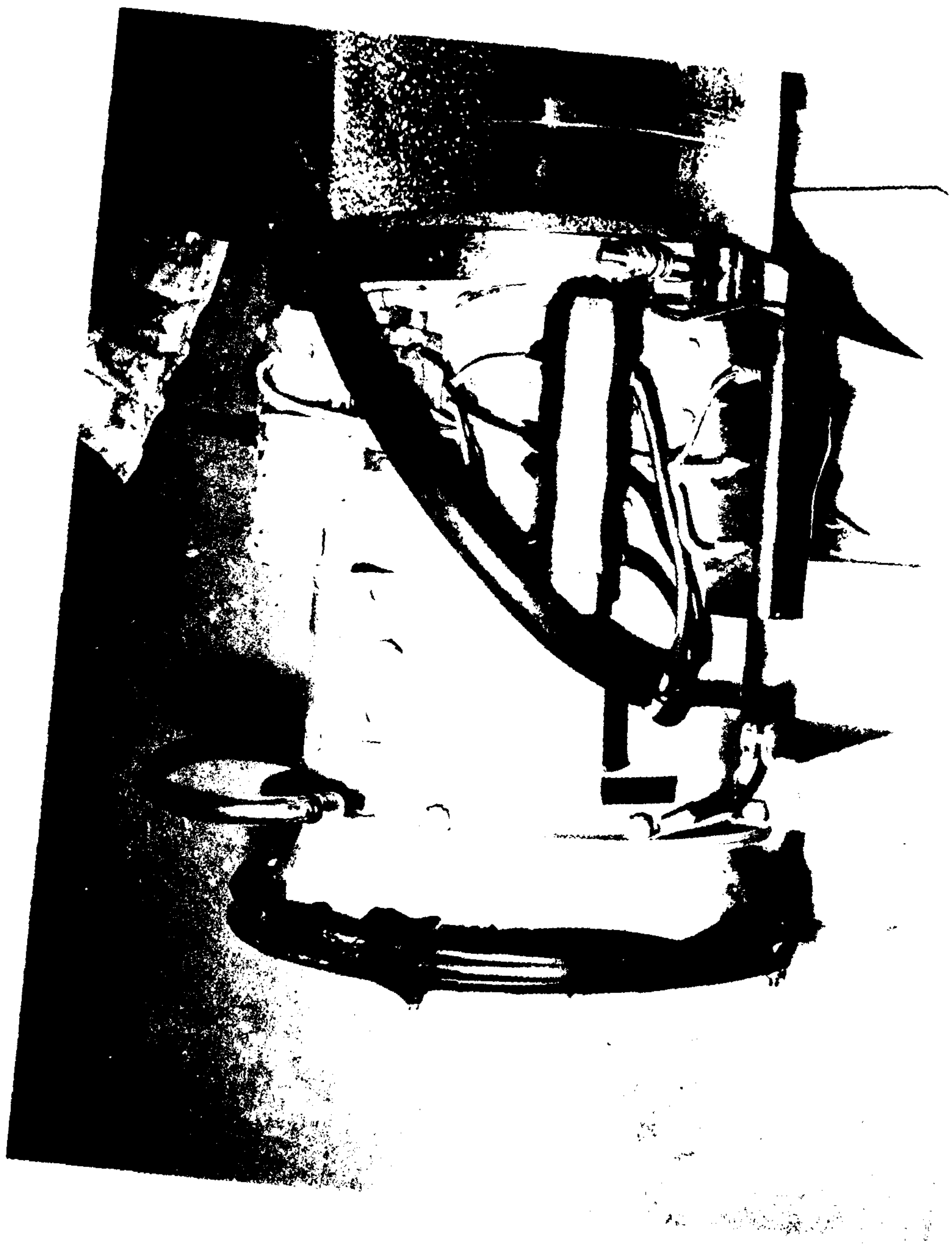


Figure 6. Position of Fan Inlet Pressure Tap

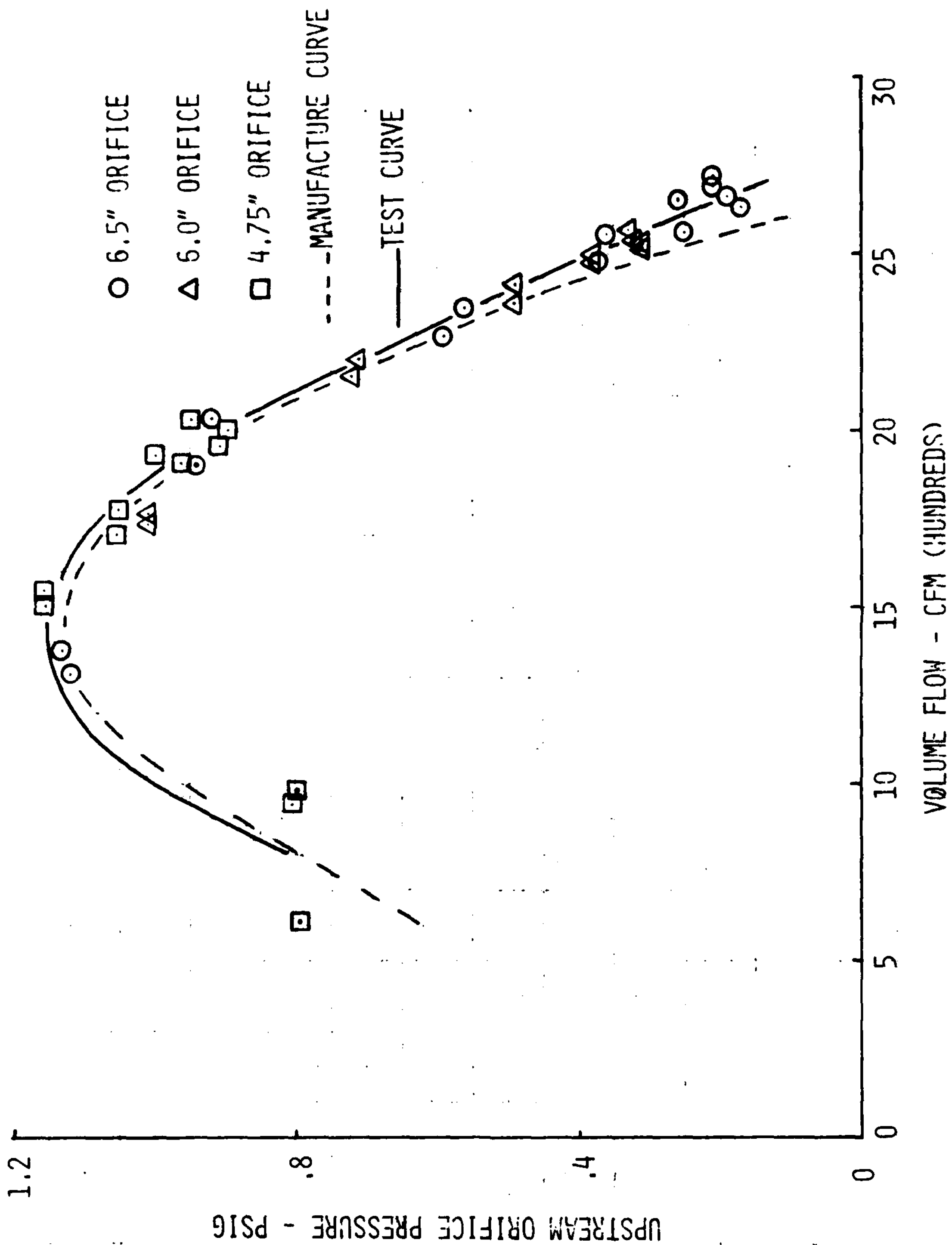


Figure 7. Comparison of Test Data with Manufactures Data at 200 Volts/400 Hz

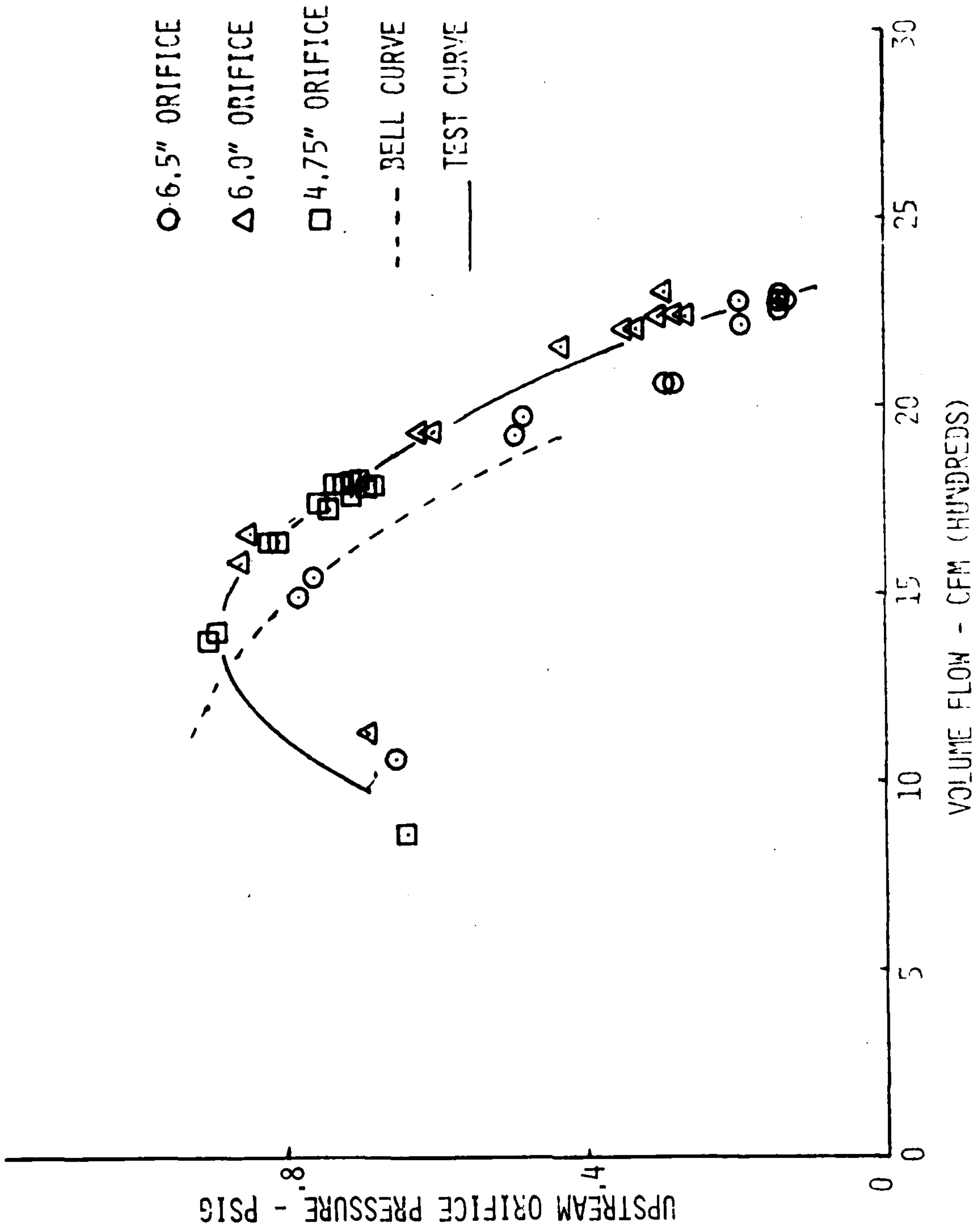


Figure 8. Comparison of Test Data with Bell Data at 200 Volts/400 Hz-Large Disc

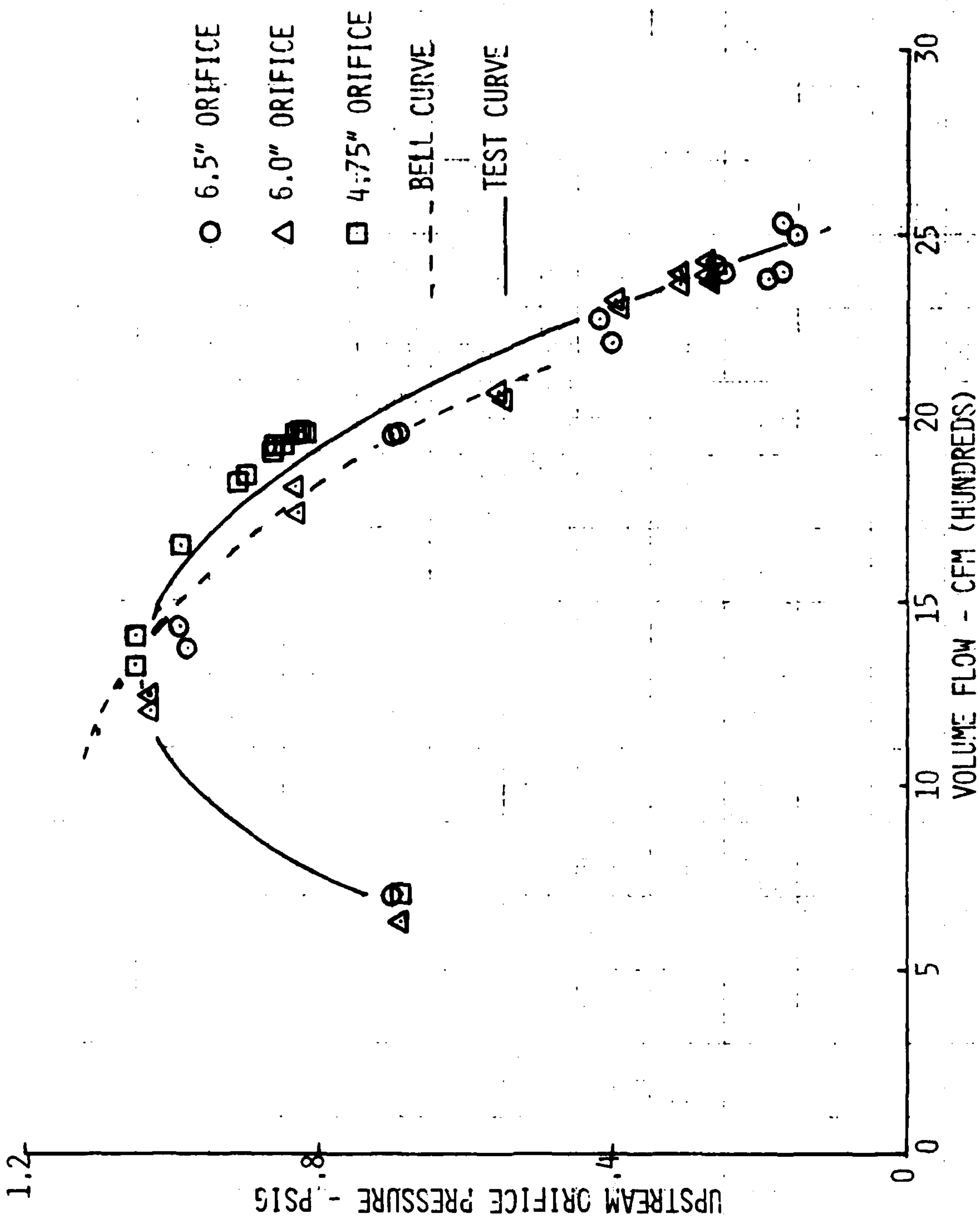


Figure 9. Comparison of Test Data with Bell Data 200 Volts/400 Hz-Small Disc

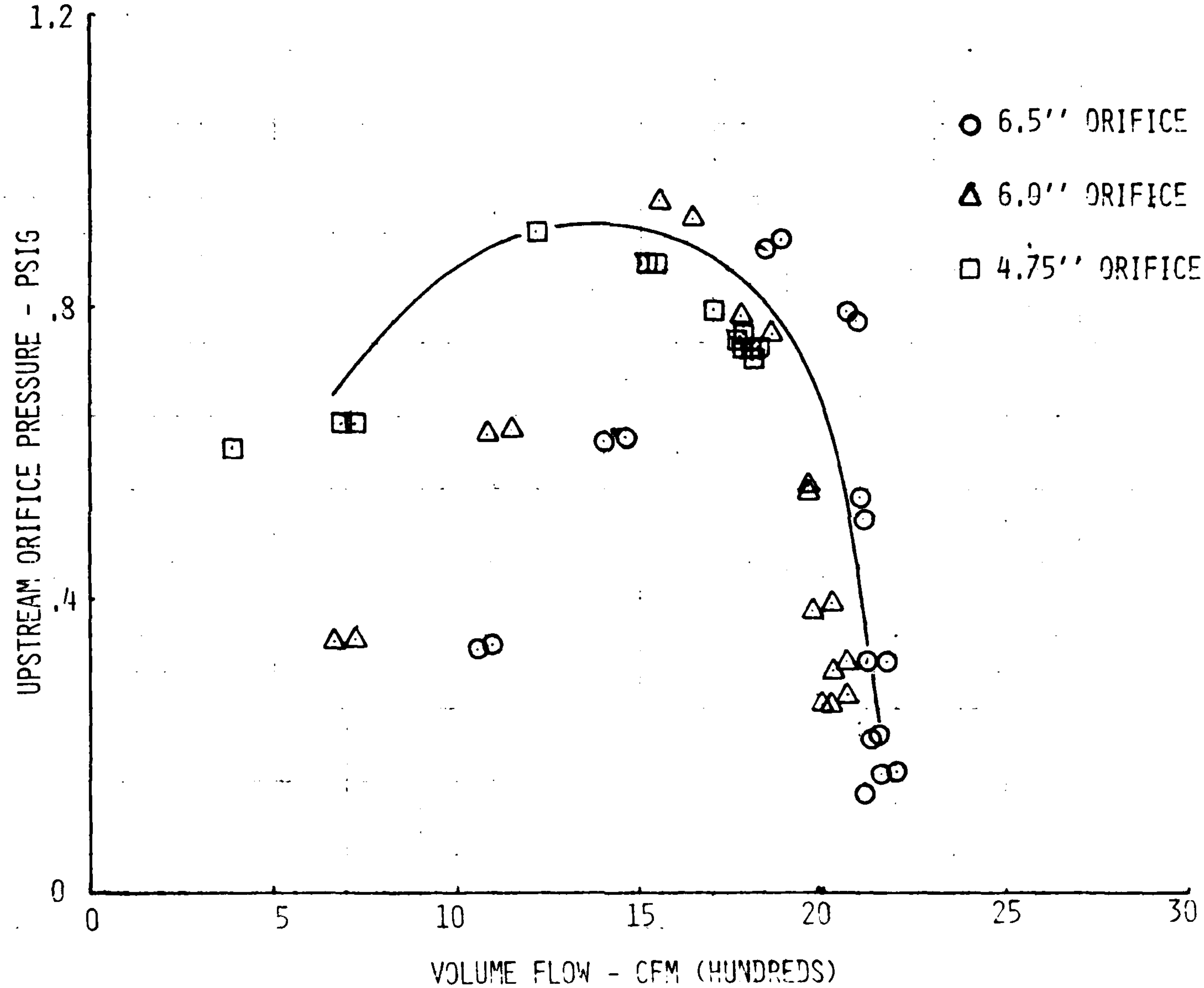


Figure 10. Upstream Orifice Pressure Versus Volume Flow at 175 Volts/ 350 Hz

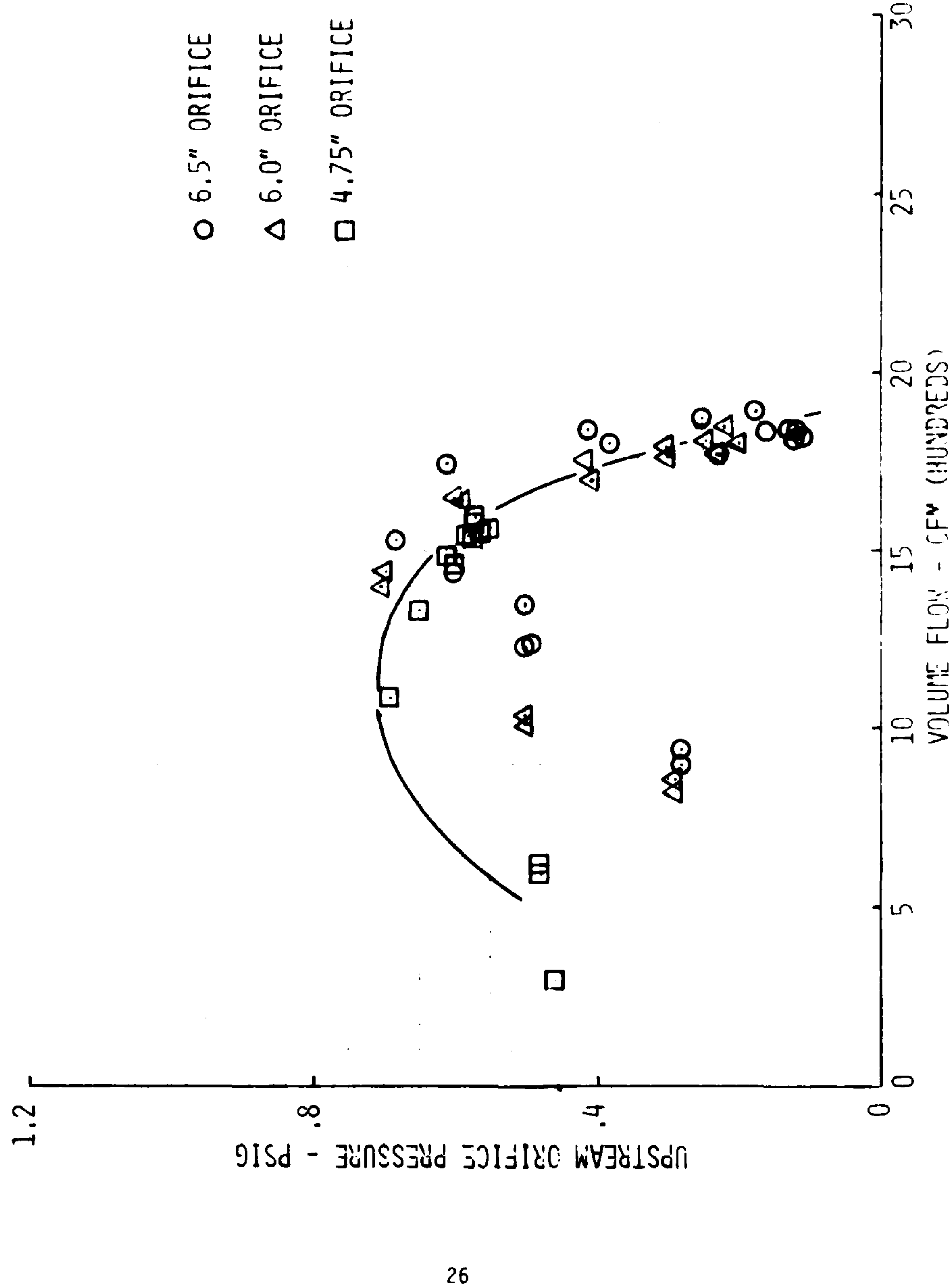
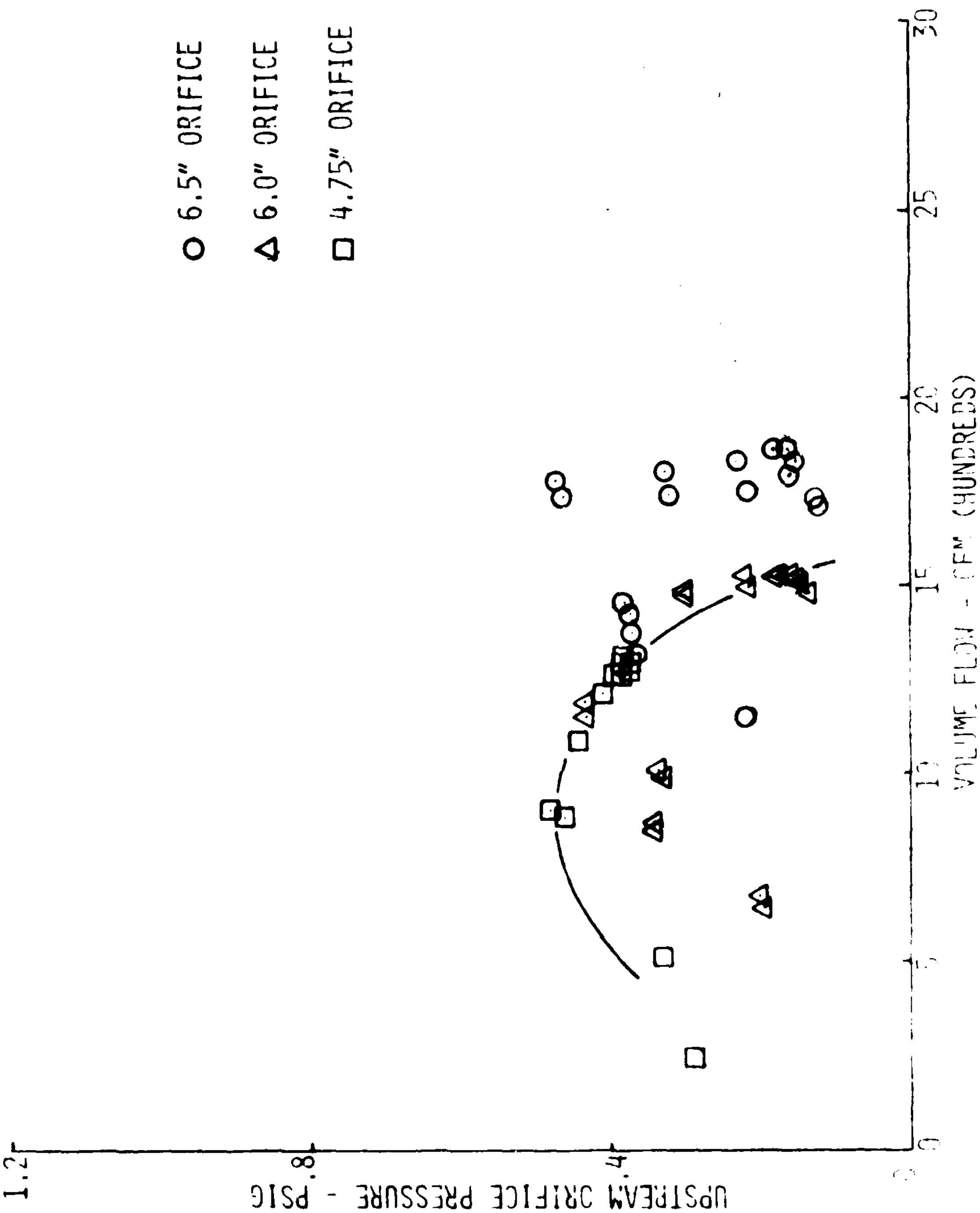


Figure 11. Upstream Orifice Pressure Versus Volume Flow at 150 Volts, 300 Hz



[illegible] Volume Flow at 125 Volts [illegible]

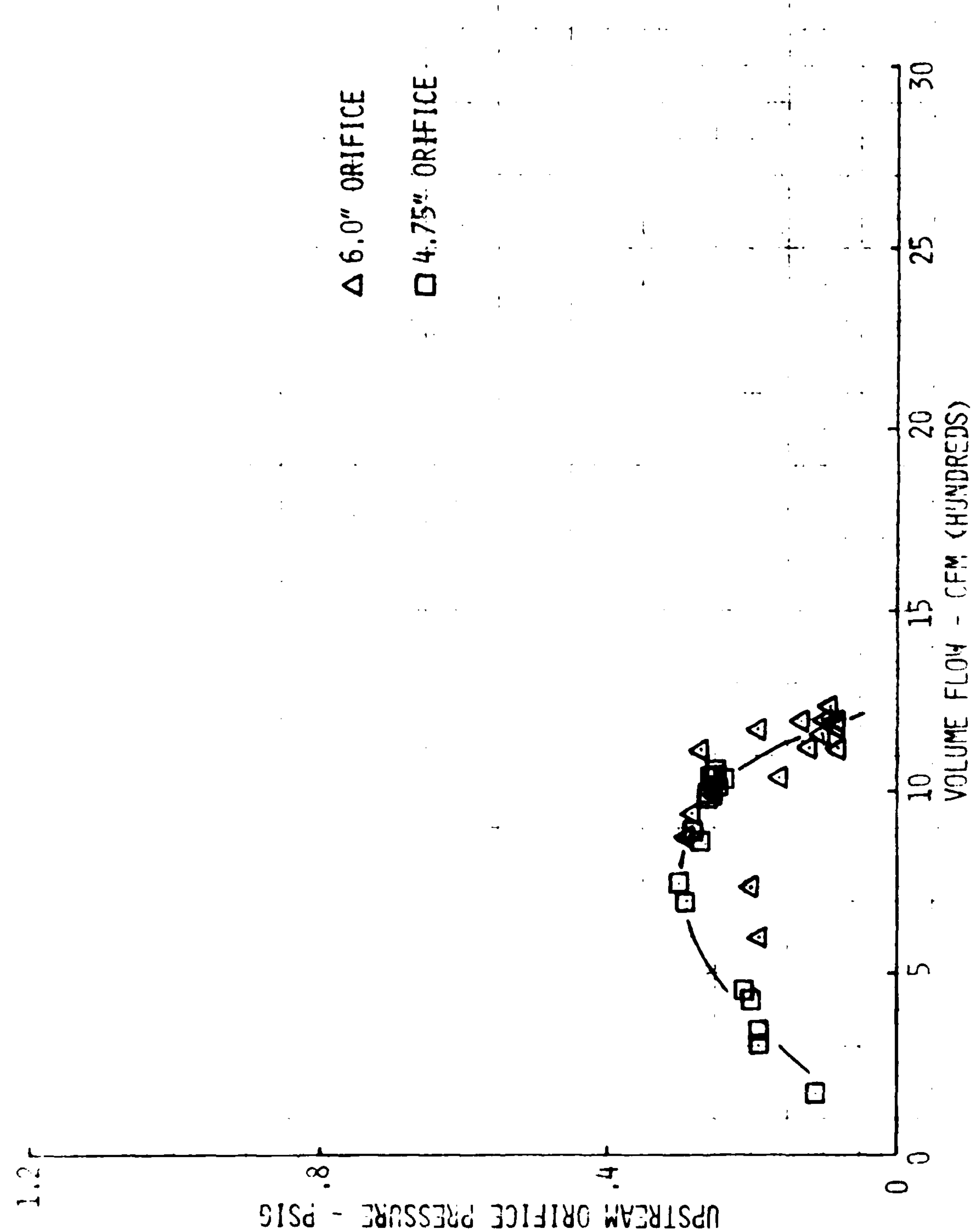


Figure 13. Upstream Orifice Pressure Versus Volume Flow at 100 Volts/ 200 Hz

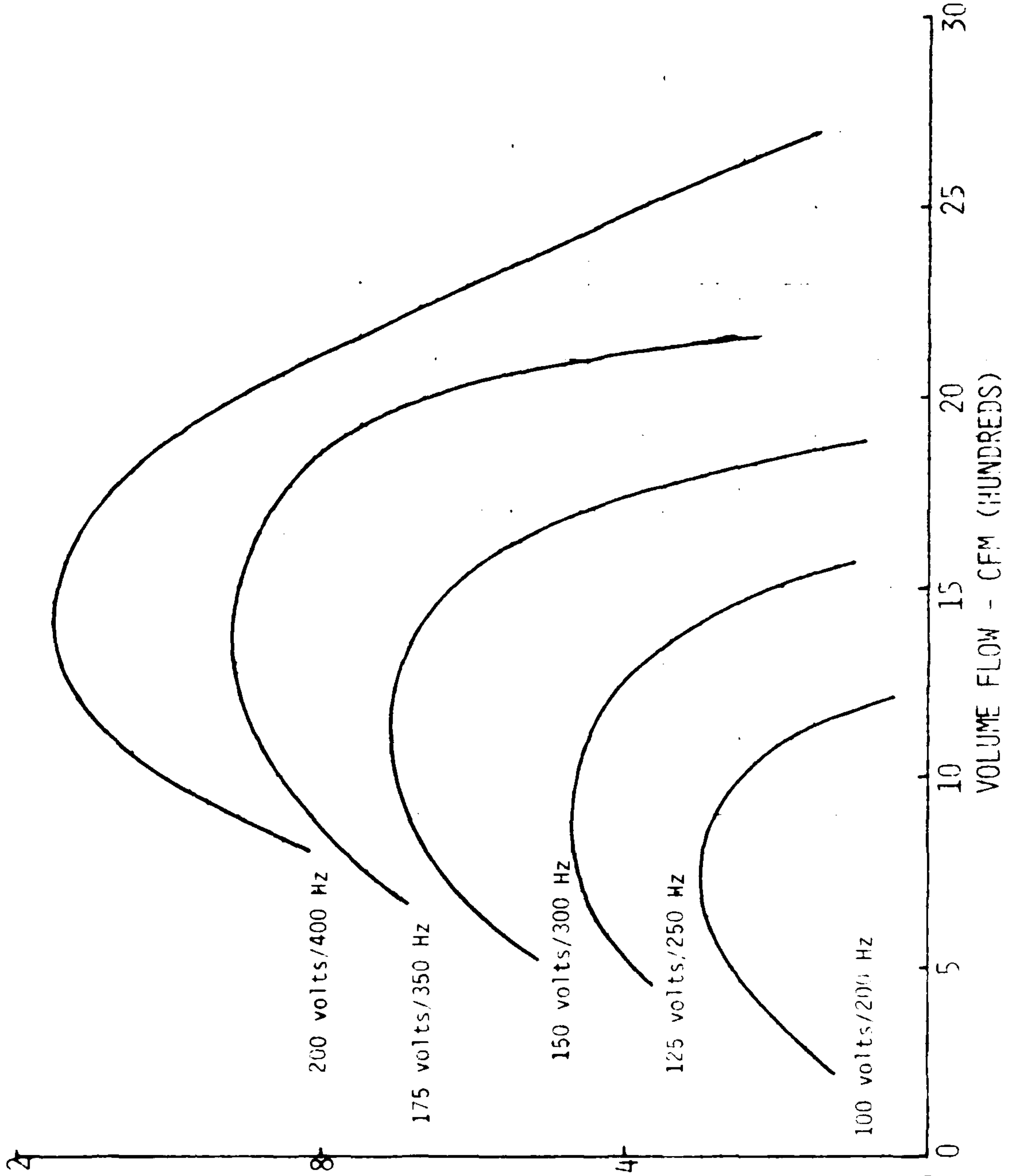


Figure 14. Composite of Upstream Orifice Pressure Versus Volume Flow

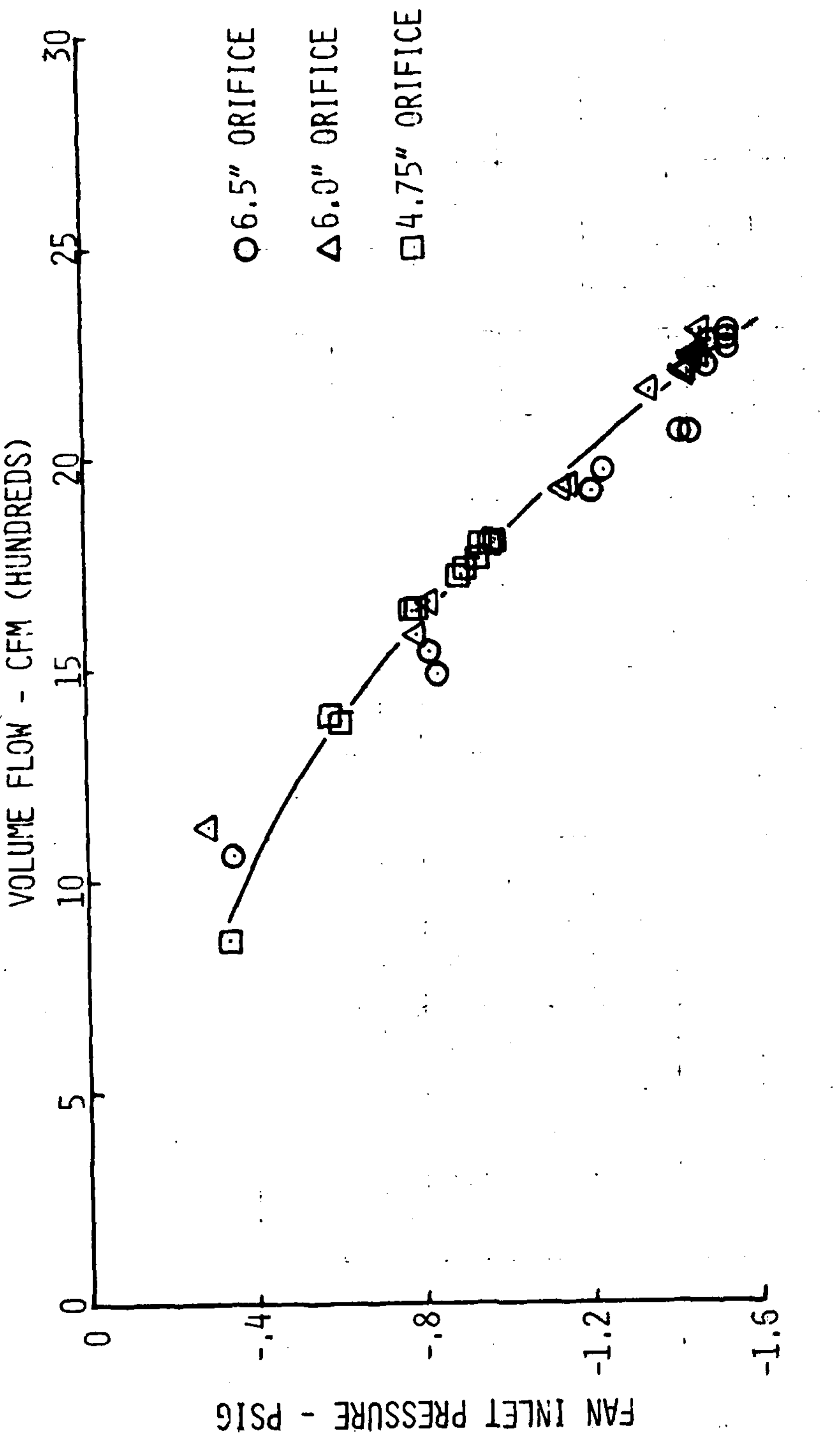


Figure 15. Fan Inlet Pressure Versus Volume Flow at 200 Volts/400 Hz-Large Disc

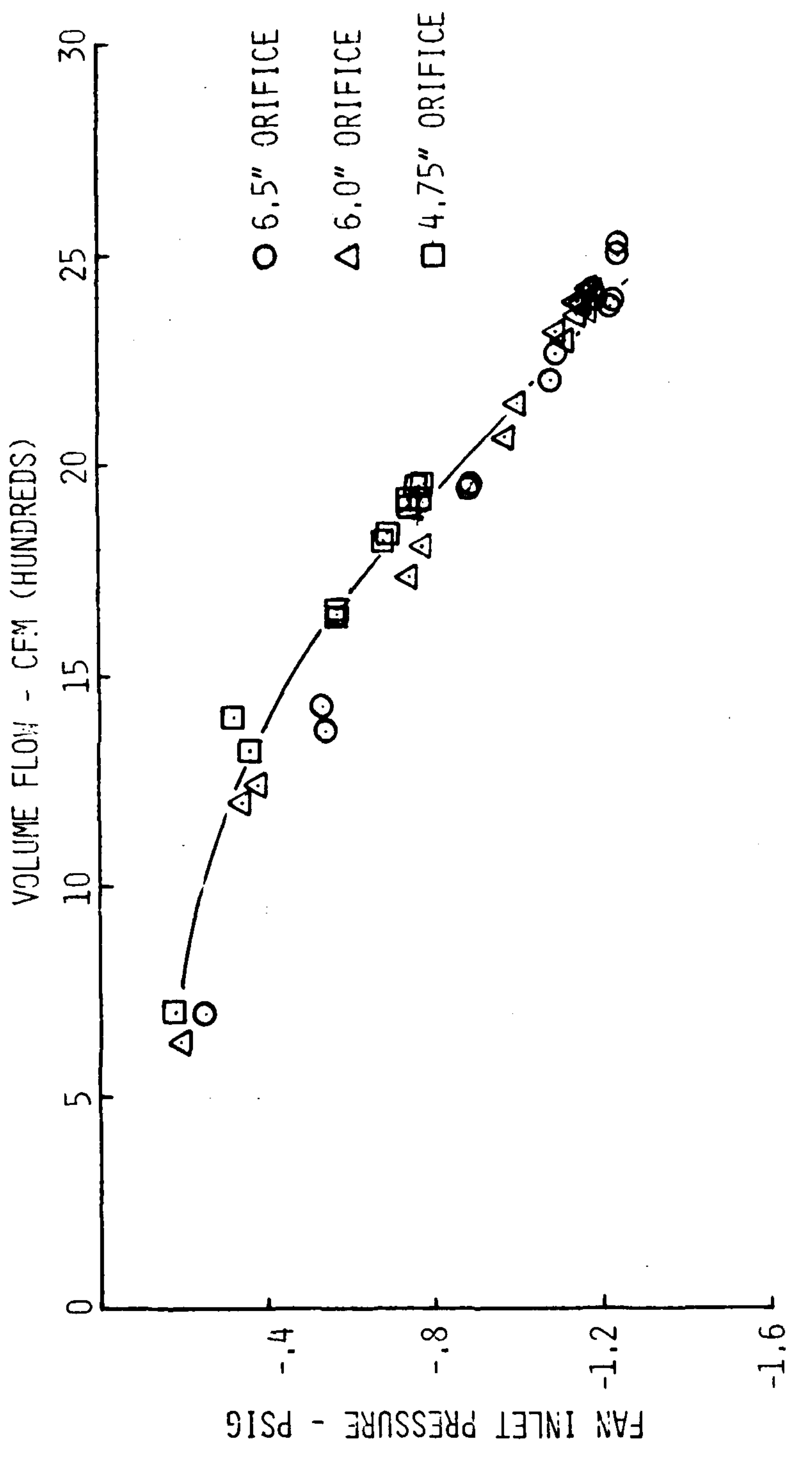


Figure 16. Fan Inlet Pressure Versus Volume Flow at 200 Volts/400 Hz-Small Disc

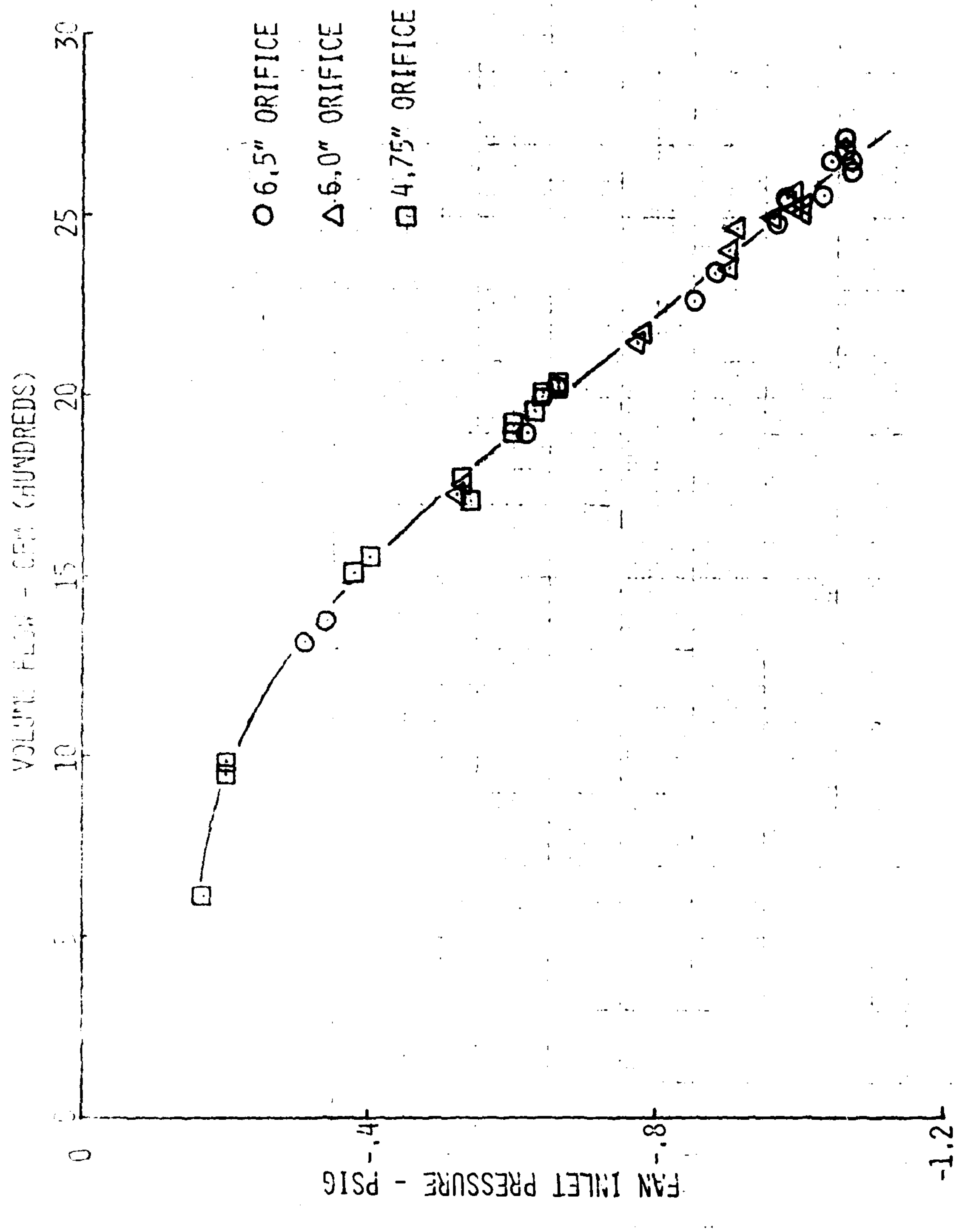


Figure 17. Fan Inlet Pressure Versus Volume Flow at 200 Volts/400 Hz

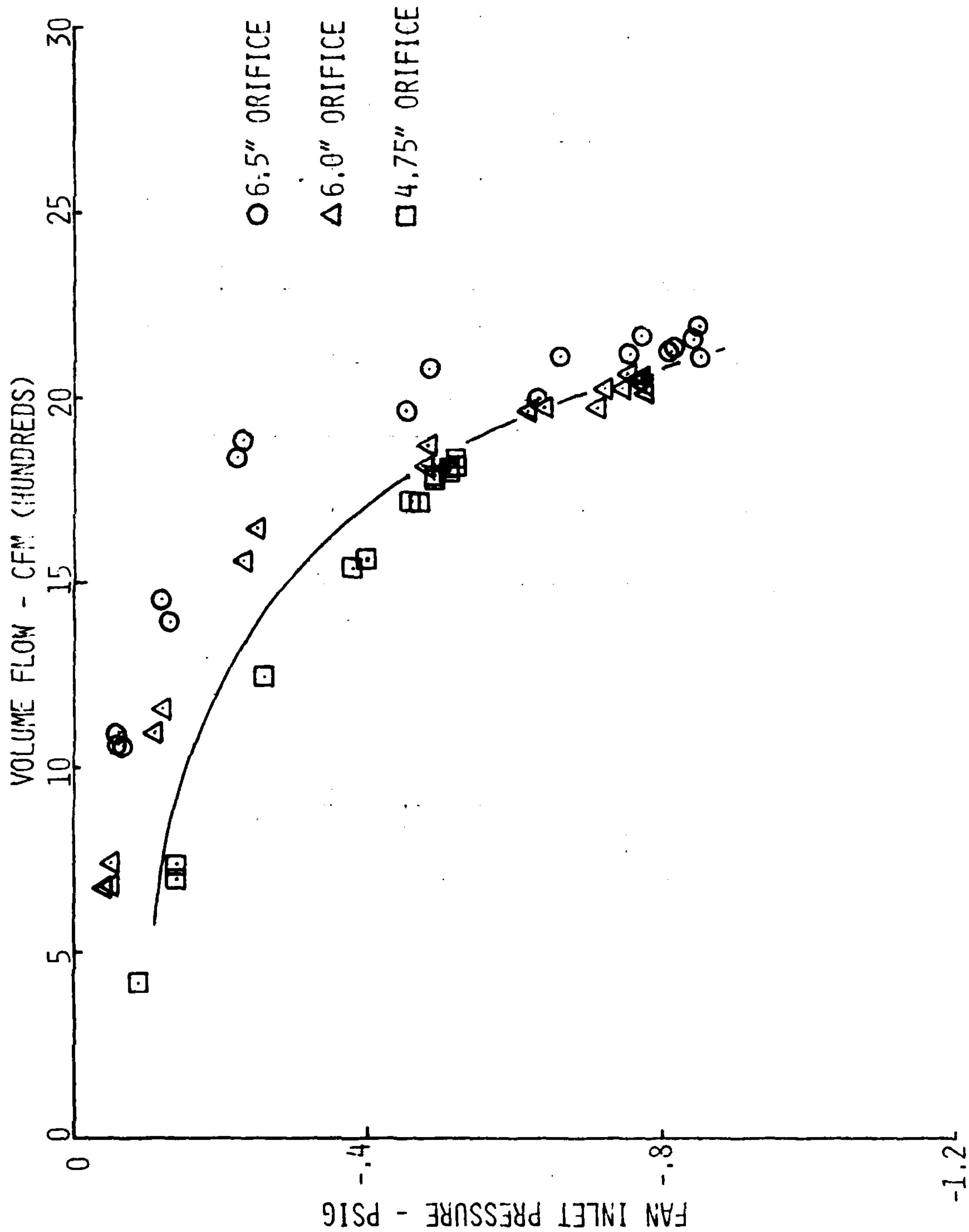


Figure 19. Fan Inlet Pressure Versus Volume Flow at 175 Volts/350 Hz

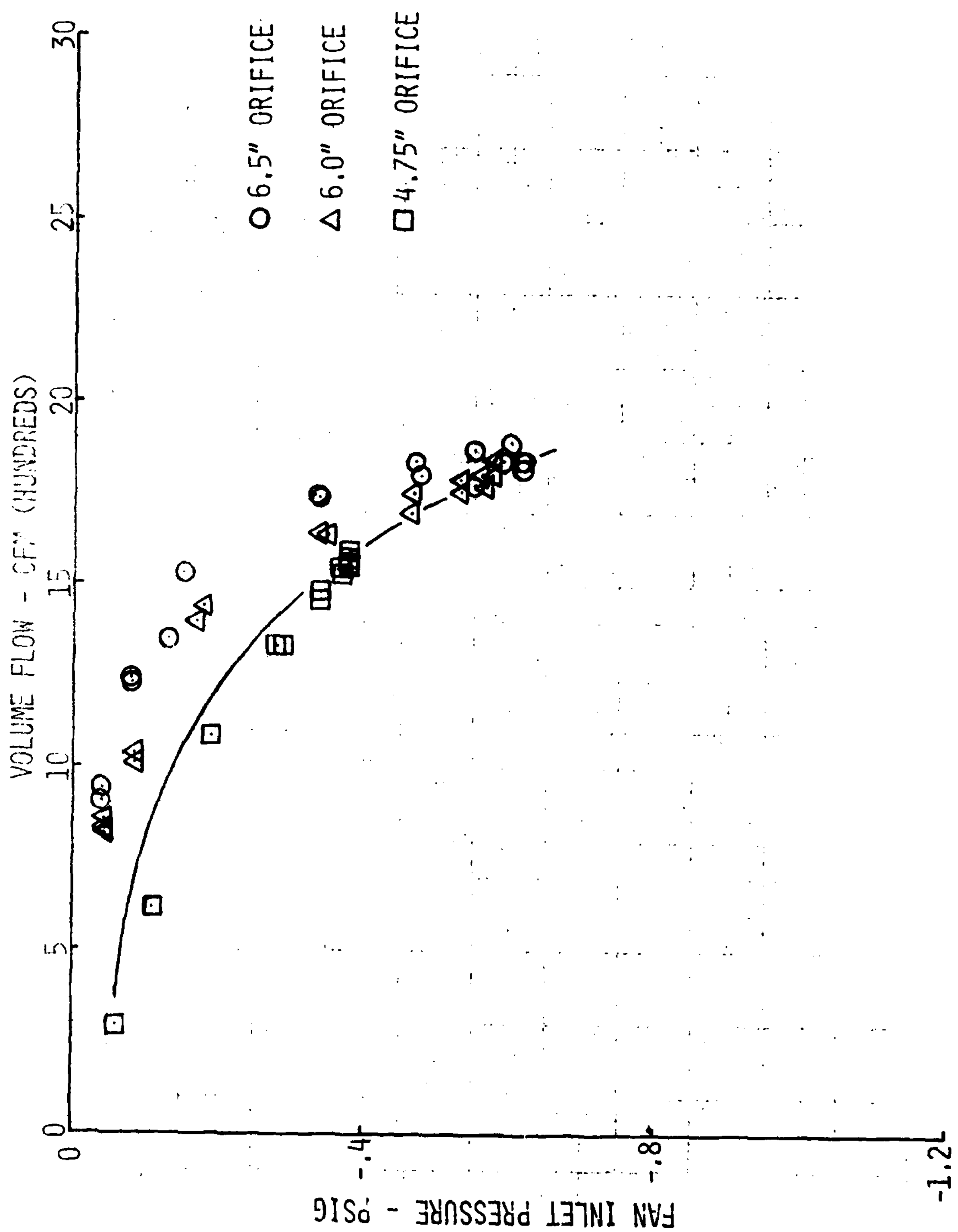


Figure 19. Fan Inlet Pressure Versus Volume Flow at 150 Volts/300 Hz

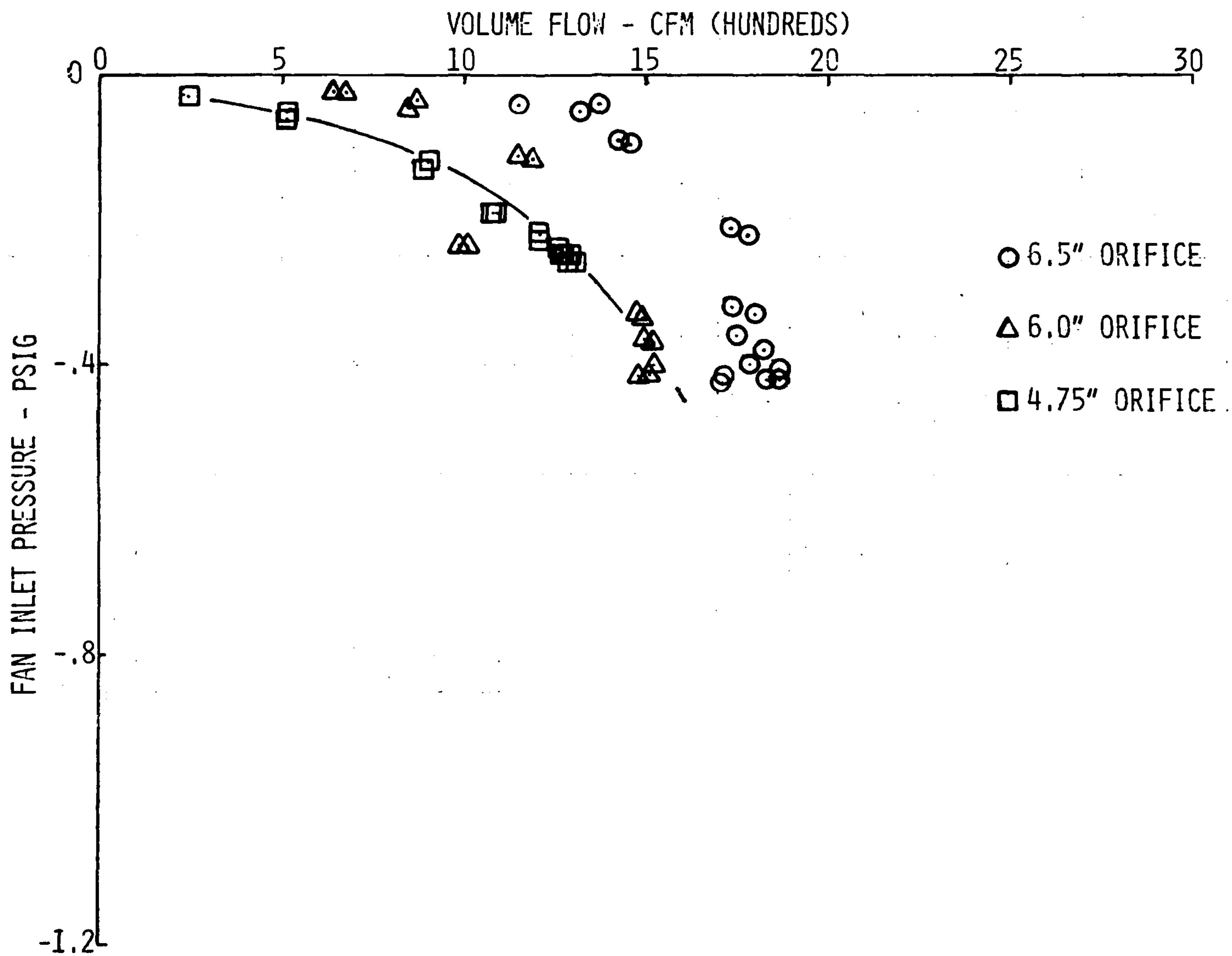


Figure 20. Fan Inlet Pressure Versus Volume Flow at 125 Volts/250 Hz

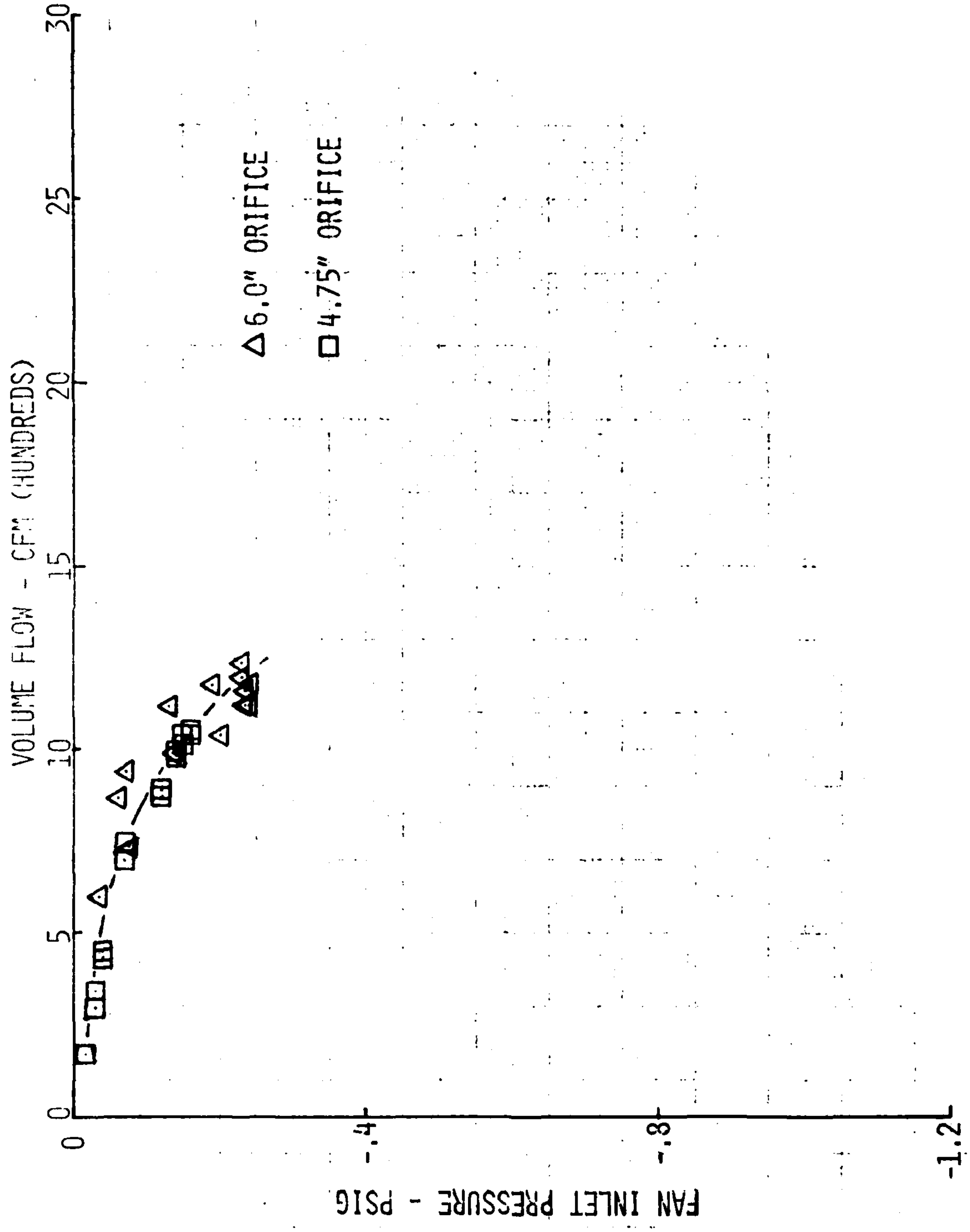


Figure 21. Fan Inlet Pressure Versus Volume Flow at 100 Volts/200 Hz

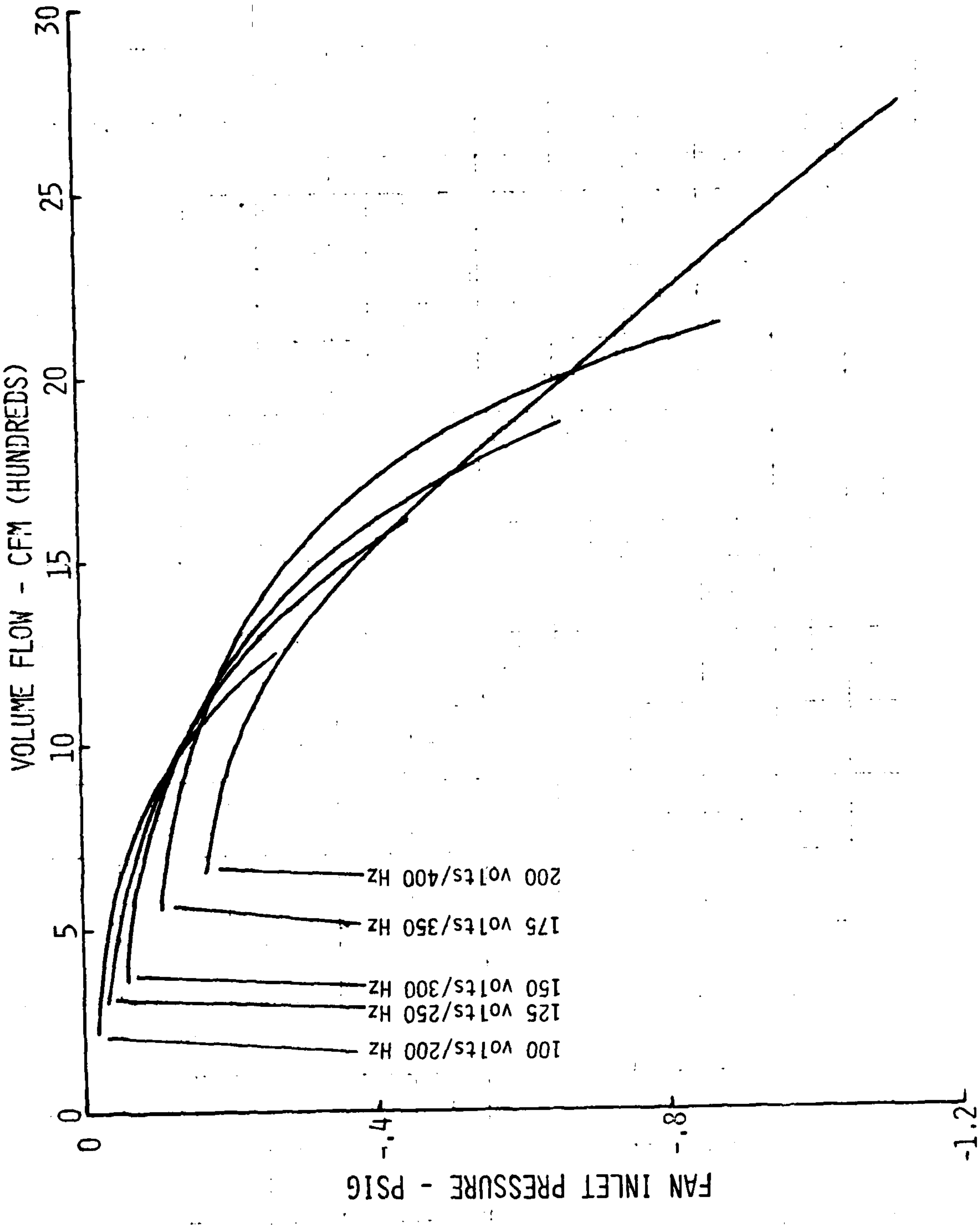


Figure 22. Composite of Fan Inlet Pressure Versus Volume Flow

APPENDIX

DATA REDUCTION METHOD

The volume flow for each test point was determined using the following equation adapted from Reference 4:

$$Q = KYd^2F_a \sqrt{\frac{(P_1-P_2)}{\rho_f}}$$

where:

Q = volume flow (ft^3/sec)

K = flow coefficient (non-dimensional)

Y = expansion factor for gas (non-dimensional)

d = orifice throat diameter (ft)

F_a = area thermal expansion factor (non-dimensional)

ρ_f = flow density (slugs/ft^3)

P_1 = upstream orifice pressure (lbs/ft^2)

P_2 = downstream orifice pressure (lbs/ft^2)

The values of orifice throat diameter, upstream orifice pressure and downstream orifice pressure were used as measured during the testing. Flow density was determined from the temperature of the air flow that was measured downstream of the orifice plate and the upstream orifice pressure. It was assumed that the temperature remained constant throughout the test rig at the time each data point was recorded. The ambient density was also found for each test using the ambient temperature and pressure record during each test. Using the perfect gas law, the flow and ambient densities were calculated as follows:

$$\rho = P/RT \quad \left(\frac{\text{Slugs}}{\text{Ft}^3}\right)$$

The area thermal expansion factor (F_a) is a quantity which accounts for the expansion of the orifice throat diameter due to heating. Since the flow temperatures were low, this factor was assumed to have no affect on the test data and was neglected. The expansion factor (Y) for the gas was found for each test point using the following equation from Reference 4.

$$Y = 1 - (0.41 + 0.35\beta^4)\ (1 - P_2/P_1)\ \left(\frac{1}{\gamma}\right)$$

where:

$$\beta = \text{orifice throat diameter ratio} = \frac{\text{throat diameter}}{\text{pipe diameter}}$$

To determine the flow coefficient (K) for each test point, it was necessary to perform an iterative solution. This is because the flow coefficient is a function of Reynolds Number. A trial value for flow coefficient was determined as follows:

$$K_{trial} = \frac{C}{1-\beta^4}$$

where:

C = coefficient of discharge

The value of the coefficient of discharge was given an arbitrary value of 0.62 from which a trial flow coefficient was calculated. Using the trial value for flow coefficient, a trial volume flow and Reynolds Number is calculated. A new value for the flow coefficient and volume flow as a function of the trial Reynolds Number can be determined. This process of calculating the volume flow and Reynolds Number is continued until the last previous calculated volume flow is within 10 CFM of the new volume flow value.

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3. A. V. Coles, Air Cushion Landing System CC-115 Aircraft, AFFDL TR-72-4, Part I, Bell Aerospace Co., Buffalo N.Y., May 1972 (Available from DDC as AD 908 559).

4. ASME Research Committee on Fluid Meters, Fluid Meters Their Theory and Application, 5th edition, ASME, 1959.

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